MASTER COPY KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

AD-A255 397

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
reprint; 1 Jan 1992 - 30 June 1992

4. TITLE AND SUBTITLE
A Plume-Induced Boundary Layer Separation Experiment

5. FUNDING NUMBERS
DAAL03-90-G-0021

6. AUTHOR(S)

R. J. Shaw and J. C. Dutton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
1206 West Green Street
Urbana, Illinois 61801

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 27558.9-EG

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

92 9 02 127

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The current paper describes an experimental investigation of a PIBLS flowfield produced by the interaction between two nonparallel, supersonic streams in the presence of a finite thickness base. The purpose of the study is to gain a better understanding of the extent to which the fluid dynamic mechanisms and interactions present in the PIBLS flowfield influence the turbulence properties of the flow. A two-stream, supersonic wind tunnel, incorporating a two-dimensional planar geometry and operating in the blow-down mode, was specifically designed to produce a PIBLS flowfield. Preliminary experiments have demonstrated that the wind tunnel is capable of producing a wide range of PIBLS flowfields by simply regulating the stagnation pressure of the lower stream (jet flow) relative to the upper stream (freestream flow). One PIBLS flowfield has been chosen in which to conduct a detailed set of measurements. This flowfield has its separation point located about $6\delta_0$ upstream of the base corner. A detailed study of this PIBLS flowfield is underway using schlieren photography and shadowgraph pictures, surface streakline visualization, surface static pressure measurements, and two-component, coincident LDV measurements.

92-24417

14. SUBJECT TERMS
plume-induced boundary layer separation; turbulent boundary layer; oblique shock wave

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

A PLUME-INDUCED BOUNDARY LAYER SEPARATION EXPERIMENT

Russell J. Shaw, Graduate Research Assistant
and
J. Craig Dutton, Professor
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

Presented at the 77th Semi-Annual STA Meeting
April 12-14, 1992
University of Notre Dame
Notre Dame, Indiana 46556

INTRODUCTION

This paper describes an ongoing experimental investigation of plume-induced, turbulent boundary layer separation as it occurs in supersonic flight. Plume-induced boundary layer separation (PIBLS) is a phenomenon that can occur on a wide range of aerodynamic vehicles during some portion of the flight regime. Examples include single-stage tactical missiles, multiple-stage missiles and rockets, high-performance fighter aircraft, and atmospheric reentry vehicles to name but a few. Figure 1 depicts PIBLS occurring on a generic two-stage missile. The existence of PIBLS in the flowfield can detrimentally influence the static stability of the vehicle, degrade the effectiveness of control surfaces, and significantly contribute to base and afterbody heating. Since these effects can severely endanger the structural integrity of the aerodynamic vehicle, PIBLS is a subject worthy of the scientific community's attention because, not only is it an important topic for basic fluid dynamics research, but a better understanding of this phenomenon can also benefit the flight performance of aerodynamic vehicles.

In addition to being dependent upon the vehicle geometry, the occurrence of this phenomenon is also dependent upon the external airstream and nozzle flow properties. The exhaust gases from a propulsive unit, either a jet engine or a rocket motor, will expand to form a plume with a diameter larger than the engine nacelle or vehicle body diameter when the static pressure at the nozzle exit plane is substantially larger than the static pressure of the surrounding airstream. The presence of this underexpanded exhaust plume deflects the freestream flow and thereby imposes an adverse pressure gradient upon the afterbody boundary layer. If the momentum of the fluid in the boundary layer is not sufficient to overcome this adverse pressure gradient, the boundary layer will separate upstream of the physical corner of the base. The upstream movement of the boundary layer separation point, resulting from the interaction of the exhaust plume with the external airstream, is called plume-induced boundary layer separation.

With the development of jet aircraft and ballistic missiles in the 1950's, PIBLS began to be recognized as a potential problem affecting the flight performance of atmospheric vehicles. The early experimental investigations of this flowfield phenomenon were conducted in the 1960's and involved laminar boundary layers. Laminar boundary layers were used because the region of the flight envelopes which encountered the most severe cases of PIBLS occurred at high altitudes where the extremely large jet-to-freestream static pressure ratios resulted in extensive regions of separation and, consequently, the laminar boundary layer did not have a sufficient development distance for transitioning to a turbulent state prior to separation. These early studies were conducted on both single nozzle [e.g., 1,2] and multiple nozzle [e.g., 3,4] base configurations, and focused primarily on understanding the impact that PIBLS had on the static stability of aerodynamic vehicles by examining both the overall physical characteristics of the separated flow region (separation pattern, separation length, angle of separation, etc.) and the resultant aerodynamic loads as a function of various flow properties (jet static pressure ratio, freestream Mach number, freestream Reynolds number, etc.), base and afterbody geometries (nozzle divergence angle, afterbody flare or boattail angle, nozzle-to-base diameter ratio, etc.), and angle of attack. These studies relied strongly upon schlieren photography, surface oil flow visualization, measurements of the resultant aerodynamic forces and moments, and, to a lesser extent, surface static pressure measurements to examine the effects caused by PIBLS.

As a result of the design evolution of propulsion units to produce higher thrust, the region of the flight envelope encountering PIBLS expanded [5] and the plume-induced separation of turbulent boundary layers became important. Experimental studies involving the plume-induced separation of turbulent boundary layers were conducted on wind tunnel models beginning in the 1970's. With one exception [6], these experiments were primarily conducted at the Aeronautical Research Institute of Sweden (FFA) [e.g., 7,8] and the University of Alabama [9-11], and have tended to focus on obtaining insight into the fundamental nature of PIBLS flowfields. While the

University of Alabama experiments involved surface pressure fluctuation measurements beneath the unsteady separation shock wave, the FFA experiments, specifically the pressure probe measurements of Agrell [12] and the one-component laser Doppler velocimeter (LDV) measurements reported by Agrell [13] and Pira and Agrell [14], attempted to make flowfield property measurements throughout the separated flow region of a PIBLS flowfield. Although for different reasons, neither the LDV technique [13,14] nor the pressure probe technique [12] were sufficiently accurate to allow a quantitative determination of the velocity field within a PIBLS region.

Beginning in the 1950's and continuing on into the 1960's, two analytical techniques were developed for calculating the flow properties behind a blunt base immersed in a supersonic flow. The two techniques were the integral or moment method [15] and the Chapman-Korst component or multicomponent method [16,17]. Although the integral method was extended to deal with a zero thickness base geometry undergoing PIBLS [18], this technique has proven to be more difficult and less versatile than the component method [19]. Aided in part by the development of computer programs by Addy [e.g., 20], the component method emerged in the 1970's as the method of choice for computing PIBLS flowfields because of its flexibility in modeling a wide range of base geometries and flow properties. The component method has been used to calculate PIBLS flowfields on aerodynamic bodies at both zero and nonzero angles of attack [e.g., 21,22]. On axisymmetric models at zero angle of attack, the component method, in general, underpredicts the extent of separation at lower jet static pressure ratios and overpredicts the extent of separation at higher jet static pressure ratios. Although the quantitative prediction of the base pressure distributions and the separation lengths are not, generally speaking, in good agreement with the experimental measurements, the qualitative trends induced by the jet static pressure ratio and the nozzle half-angle are predicted reasonably well by the component method for both symmetric and asymmetric PIBLS flowfields.

With the advent of supercomputers and better numerical algorithms, the numerical modeling of PIBLS flowfields using Navier-Stokes (N-S) methods has developed over the past decade and stands today as an area of major interest. The Navier-Stokes investigations which have calculated PIBLS flowfields [e.g., 23,24], in general, underpredict the extent of separation, underpredict the separation angle, and underpredict the base and afterbody pressure distributions. Even when one of these studies was successful at quantitatively predicting one or more of these four features, the remaining features were not in agreement with the experimental data. Although the quantitative prediction of these features, in general, is in poor agreement with the experimental measurements, the parametric trends induced by the jet static pressure ratio and the nozzle half-angle are predicted reasonably well by the N-S methods.

A majority of the N-S studies [e.g., 25,26] have emphasized the need for better turbulence modeling throughout the plume-induced, separated region of the flowfield in order to achieve a more accurate prediction of the flow. As just discussed, the extent of the separation zone, the angle of separation, and the surface static pressure distributions over the base and afterbody have formed the basis for comparing N-S calculations with experimental data. Although these features allow a determination to be made of the general accuracy of a N-S prediction, they do not permit a direct evaluation of a turbulence model's ability to predict the turbulence structure throughout a plume-induced, separated flowfield. Accurate measurements of mean velocity and turbulence quantities obtained throughout a PIBLS flowfield are necessary in order to evaluate the accuracy of a turbulence model. This is exactly the information that the present work is directed at obtaining.

The experimental investigation described herein will provide a better understanding of the mechanisms and interactions present in a PIBLS flowfield primarily by measuring the mean and fluctuating components of velocity with an LDV system. Schlieren photographs and shadowgraph pictures, surface flow visualization, and mean and fluctuating wall static pressure measurements have also been made of the PIBLS flowfield. By gaining a better understanding of the fluid

dynamic processes present in a PIBLS flowfield, it is felt that the existence of this phenomenon can more accurately be predicted and thus technological improvements can be made to aerodynamic vehicles which will delay, control, or totally eliminate either PIBLS or the adverse effects associated with its occurrence.

FLOW FACILITY AND WIND TUNNEL DESCRIPTION

The experiments conducted in this study are performed using the flow facility located in the Gas Dynamics Laboratory. The flow facility consists of a tank farm with a storage capacity of approximately 146 m^3 and two air compressors: an Ingersoll-Rand compressor which produces 0.68 kg/s at 960 kPa and a Gardner-Denver compressor which delivers 0.33 kg/s at 760 kPa.

A two-stream, supersonic wind tunnel was specifically designed to produce plume-induced, turbulent boundary layer separation in the test section. The small-scale wind tunnel incorporates a two-dimensional planar geometry and operates in the blowdown mode. The geometry of the wind tunnel is shown in Figures 2 and 3. Figure 2 is a cross sectional view of the wind tunnel test section. Figure 3 is a photograph of the actual PIBLS wind tunnel with one side wall removed. In order to minimize pressure losses, the cross sectional area of each stream was scaled so that the Mach number of the flow would not exceed 0.2 at any location upstream of the nozzle blocks. The region of supersonic flow in each stream is produced with a fixed nozzle block whose diverging contour was calculated using the method of characteristics nozzle design program NOZCS. The height of the base is 1.27 cm and the angle between the two streams is 40 degrees (see Figure 2). The width of each stream is 5.08 cm, except at the inlet of the tunnel where each stream is 7.62 cm wide. Optical access to the test section is provided by a removable glass window assembly mounted in each of the two side walls of the tunnel.

As just stated, the angle between the two streams is 40 degrees. A brief discussion of the method used to arrive at this value is in order since choosing this parameter was the most critical aspect in the design of the wind tunnel. In essence, the concept was to choose an angle between the two streams which would be sufficient to deflect the discriminating streamline present in the shear layer emanating from the separation point (assumed to be at the corner of the base) in the upper stream at an angle of about 15 degrees (discussed below) with respect to the freestream flow direction. The location of the discriminating streamline was calculated using the restricted model of the multicomponent method [27,28] modified to include the reattachment criterion of Addy [29] with a reattachment coefficient of 0.9. All of the computations were done for a single operating condition: an upper stream stagnation pressure of 517 kPa and a lower stream stagnation pressure of 345 kPa. By summarizing data taken from experiments on turbulent boundary layer separation ahead of forward-facing steps for Mach numbers ranging from 1.0 to 6.0 and step heights of at least one boundary layer thickness, Zukoski [30] found that the inner surface of the shear layer bounding the separation zone formed an angle of 13 degrees with respect to the freestream flow direction and the outer surface formed an angle of 16.5 degrees. Since separation in the forward-facing step experiments is produced by a solid geometric boundary and separation in the PIBLS study is caused by a compliant aerodynamic boundary, there is an intrinsic difference between the two flowfields [31] and therefore it was deemed unnecessary to know the precise location of the discriminating streamline in the forward-facing step experiments. The decision was made to simply equate the angle of the discriminating streamline in the PIBLS study to a value slightly above (approximately 15 degrees) the average of the angles between the upper and lower surfaces of the shear layer from the forward-facing step data of Zukoski. The angle of the discriminating streamline in the upper shear layer of the PIBLS investigation was computed to be 14.7 degrees for an angle between the two streams of 39 degrees, and 15.5 degrees for an angle of 40 degrees. The decision was made to opt for the 40 degree angle, and, in so doing, it was hoped that there would exist sufficient latitude in throttling or unthrottling the lower stream away from the 345 kPa stagnation pressure design point so as to achieve PIBLS.

Preliminary investigations of the flowfield using schlieren photographs, shadowgraph pictures, and surface oil flow visualization have shown that plume-induced, boundary layer separation can be produced in the wind tunnel designed for this investigation (see Figures 4 and 5). Acceptable PIBLS flowfields can be produced by varying the stagnation pressure of the lower stream over the approximate range of 255 kPa to 186 kPa while maintaining a stagnation pressure of 517 kPa in the upper stream. This corresponds to jet static pressure ratios of approximately 2.4 to 1.7. In these flowfields, a boundary layer develops on the bottom wall of the upper stream and forms a free shear layer after undergoing separation somewhere upstream of the upper base corner. It is interesting to note that an angle of approximately 15 degrees (i.e., the value used in the design) results from averaging the angles made by the inner and outer surfaces of this shear layer. The separation point is nominally located 1.9 cm (about $6\delta_o$) forward of the upper base corner (as determined by surface oil flow experiments) at a lower stream stagnation pressure of 255 kPa (p_j/p_∞=2.4). (The surface flow technique determines the downstream boundary of the region over which the unsteady shock wave oscillates [32].) The nominal location of the separation point can be reduced to approximately 0.64 cm (about $2\delta_o$) forward of the upper base corner if the stagnation pressure in the lower stream is throttled to about 186 kPa (p_j/p_∞=1.7). The only two regions having a spanwise variation in the streamwise location of the separation line, as delineated by the surface oil flow experiments, are located adjacent to each wind tunnel side wall and extend for 0.97 cm from each side wall. Since the separation line is straight and perpendicular to the freestream flow direction over the inner 3.18 cm of the tunnel width, the flowfield appears to be reasonably two-dimensional over this inner region.

From the review of experimental work on the plume-induced separation of turbulent boundary layers, the separation process has been shown to be unsteady on wind tunnel models. Separation shock wave unsteadiness has also been reported on actual flight vehicles undergoing PIBLS [33, 34], although it is unknown whether the mechanism causing the unsteadiness on the wind tunnel models is the same mechanism causing the unsteadiness on flight vehicles. The PIBLS flowfield produced in the wind tunnel of this investigation also exhibits an unsteady separation process. The streamwise extent of the unsteadiness (as indicated by separation shock motion) has been estimated from schlieren observations to be on the order of several boundary layer thicknesses. The detailed motion of the unsteady separation shock wave also appears under schlieren observation to be very similar to the unsteadiness described in the PIBLS experiments of Boggess [9] and Doughty [10,11], i.e. a quasi-random, aperiodic movement of the shock. This unsteadiness clearly poses a problem when making LDV measurements because it is impossible to distinguish between velocity fluctuations caused by turbulent eddies and velocity fluctuations caused by the gross translational movement of the separation region. The conditional sampling approach to be used to address this LDV measurement problem is described in the following section.

RESULTS

Although a range of PIBLS flowfields can be produced in the wind tunnel designed and built for this investigation, only one such flowfield has been chosen in which to conduct the detailed LDV measurements. The flowfield chosen for the preliminary measurements presented in this paper is produced by setting the upper and lower stream stagnation pressures at approximately 517 kPa and 255 kPa, respectively. The foot of the separation shock wave is then nominally located 1.9 cm (about $6\delta_o$) upstream of the base corner and thus, based upon previous experimental results [7], the separation process should be a free-interaction at this location.

Schlieren/Shadowgraph Visualizations

Visualization of the near-wake flowfield has been documented using shadowgraph pictures and schlieren photographs. Both systems were configured with components in the standard "Z"-shaped arrangement where the light source and receiving optics were positioned as close as possible to the collimated light beam passing through the wind tunnel test section. The schlieren system uses a Xenon Model 457 Micropulser light source having a spark duration of approximately 1.4 microseconds when operated in the single pulse mode. The shadowgraph system uses a Xenon Model 437B Nanopulser light source having a spark duration of approximately 25 nanoseconds in the single pulse mode. The collimated light was created using two, 30.48 cm diameter, 243.8 cm focal-length mirrors. The receiving optics in the schlieren setup consisted of a horizontally mounted knife-edge, and a "smoked" glass collection plate for viewing the image or a Polaroid film holder for obtaining a permanent photograph. The receiving optics in the shadowgraph setup consisted of a Nikon Model F2 35 mm camera. Figure 4 shows a typical schlieren photograph of the PIBLS flowfield while Figure 5 shows a typical shadowgraph picture. When comparing the two prints, it is quite evident that the shadowgraph system, with the 25 nanosecond light pulse, resolves much smaller turbulence scales throughout the flowfield than does the schlieren system.

Mean Static Pressure Measurements

Mean wall static pressure measurements have been obtained from static pressure taps mounted in the top, bottom, and base surfaces of the center partition, as well as from a side wall assembly that has been extensively instrumented with static pressure taps. The top surface of the center partition has twenty-nine pressure taps installed at a spanwise station located 0.475 cm off the wind tunnel centerline. (The taps could not be placed on the centerline because two miniaturized, high-frequency response, piezoresistive pressure transducers are mounted along the centerline.) Beginning 0.318 cm upstream of the base plane and extending to 3.81 cm upstream of the base plane, the taps are located every 0.159 cm; the taps are uniformly spaced every 0.635 cm starting at 3.81 cm upstream of the base plane and continuing to 7.62 cm upstream of the base plane. The bottom surface of the center partition has four pressure taps mounted along the same spanwise station as the top surface. The location of these taps begins 0.318 cm upstream (measured local to the Mach 1.5 flow direction) of the base plane and continues to 1.27 cm upstream of the base plane in intervals of 0.318 cm. The base plane of the center partition has four pressure taps mounted along a spanwise station 0.556 cm off the wind tunnel centerline. Beginning 0.419 cm from the top surface of the center partition, the taps are located every 0.203 cm.

The side wall static pressure measurement assembly is a rectangular aluminum insert which is used for conducting mean static pressure measurements over the entire PIBLS flowfield. In order to do so, one of the window assemblies is removed from the tunnel side wall and the pressure measurement assembly is installed in its place. This assembly contains 425 static pressure taps uniformly distributed, 0.229 cm between centers, over the main region of interest in the flowfield. The region of interest was established from schlieren photographs and is shown in Figure 6.

Pressure measurements from the pressure taps in the center partition, the side wall insert, and the pitot probes at the nozzle entrances are acquired by connecting the pressure taps to a Pressure Systems Incorporated Model DPT 6400 digital pressure transmitter using clear flexible vinyl tubing. The pressure transducers of the DPT 6400 were calibrated with a Bell & Howell dead weight tester. Figure 7 shows a two-dimensional surface plot of the mean static pressure field taken from the side wall insert. The general trends of a constant pressure in the base region and a pressure increase in the initial portion of the wake redevelopment region downstream of the

point of confluence between the two shear layers is evident in the data. However, the strong pressure gradients across the separation shock wave and the recompression shock waves emanating from the point of confluence between the two shear layers are significantly smeared over a sizeable area due to the unsteadiness of the separation process. These mean static pressure measurements, along with those shown in Figure 8, provide strong motivation for conducting conditional sampling of the LDV data. Figure 8 shows the mean static pressure measurements taken from the pressure taps in the top surface of the center partition and the mean static pressure measurements taken from a horizontal row of pressure taps, 0.114 cm above the top surface of the center partition, in the side wall insert. The two rows of measurements differ over the intermittent region of the separation shock motion and over the separated region confined between the intermittent region and the base plane.

Conditionally Sampled LDV Measurement Approach

The mean and fluctuating velocity components will be measured with the LDV over the entire region of interest in the PIBLS flowfield. Also, measurements in the turbulent boundary layer and the adjacent inviscid flow for both streams forward of the separation location will be made. In order to obtain LDV measurements throughout an unsteady PIBLS flowfield, a means must be found to overcome the problems posed by the unsteady separation shock motion. There are essentially two options: either a method must be found to stabilize the separation shock or a conditional sampling technique must be developed for acquiring the data. There are several passive techniques available which have been used to stabilize shock wave motion on airfoils in transonic flow [e.g., 35]. Unfortunately, it is not at all obvious that these techniques will apply to a supersonic two-stream interaction. In addition, applying blowing or suction to the boundary layer, or any other approach that would produce the same effect, will perturb the flow in the separated region and hence is unacceptable. Previous work by Doughty [11] has shown that the length scale of the unsteadiness can be reduced by approximately 80% in a PIBLS flowfield by positioning a small wire protuberance of circular cross section near the separation point. This method was implemented in the wind tunnel designed for the present PIBLS study and the resulting flowfields were examined qualitatively using schlieren photography. Although a reduction in the length scale of the unsteady separation shock wave motion was observed, this approach was deemed inappropriate for the present PIBLS study because the presence of the small wire protuberances appeared to alter the turbulence structure in the resulting separated shear layer. Therefore, a conditional sampling technique for acquiring and analyzing the LDV data is under development.

The approach of conditionally sampling LDV data using surface pressure measurements as a means for locating the separation shock wave has been reported in the experiments of Kussoy, et al. [36]. In this study, six fast-response pressure transducers were used to conditionally sample LDV measurements taken from two unsteady separated flowfields produced by a cylinder-flare body. The axis of the 30 degree flare was canted at an angle relative to the axis of the cylinder in order to produce a region of three-dimensional separation. Flowfields for canted angles of 5 degrees and 23 degrees were examined by simultaneously measuring and recording the pressure sensed at all six pressure transducers with every LDV measurement. However, the authors reported only one rather simple approach for conditionally sampling the data. This approach basically consisted of dividing the transducer array region into two sections using the pressure sensed at the transducer located beneath the average shock position. This transducer, called the center transducer, was identified by observing shadowgraph movies of the shock unsteadiness. For each LDV measurement location, the ensemble-averaged mean and standard deviation of the pressure (P_w and σ_{pw}) were computed using the pressure data recorded from the center transducer. Then, for each LDV measurement location, all LDV realizations having an associated pressure level greater than $P_w + \sigma_{pw}$ were collected and labeled as the "shock forward" data set. Likewise, all LDV realizations having an associated pressure level less than $P_w - 0.5\sigma_{pw}$ were collected and labeled as the "shock back" data set. Using this conditional sampling technique on the data from both flowfields, Kussoy, et al. [36] reported the mean streamlines constructed from the ensemble-

averaged velocity components, contours of the mean streamwise velocity, and the streamwise distribution of the maximum turbulent kinetic energy (k_{max}) for all three data sets: the "shock forward" data set, the "shock back" data set, and the data set constructed from ensemble-averaging all of the measurements. The authors pointed out that, although the recirculating core within the separated region does move streamwise along the cylinder, there is little change in the appearance of the mean velocity field as the shock wave fluctuates between its upstream and downstream positions. The streamwise distributions of the maximum turbulent kinetic energy for both flowfields show that the largest difference between the three data sets occurs in the intermittent region over which the shock wave oscillates.

The conditional sampling technique, more accurately described as a conditional analysis technique, used in the current work is being implemented in the following manner. Two Kulite Model XCS-062-15G pressure transducers have been mounted flush to the surface of the lower wall of the Mach 2.5 stream as shown in Figure 9. The transducers are located 1.91 cm and 1.65 cm upstream of the base plane, and are both within the intermittent region of the separation shock wave motion. The flowfield to be studied will be selected by adjusting the stagnation pressure of the lower stream such that the two pressure transducers are positioned on either side of the average separation shock location. The two time history traces, one trace created from each of the two pressure transducers during the course of a tunnel run, will be used to define the instantaneous location of the separation shock wave by implementing a two-threshold algorithm [37,38] designed to determine whether the shock wave is upstream or downstream of each transducer. There are three regions in which the shock could be located at any instant in time: the region upstream of both pressure transducers, the region in between the two transducers, and the region downstream of both transducers. LDV data acquisition from a TSI Model IFA 750 digital Doppler signal processor is controlled using FIND software running on a Gateway 2000 personal computer, which is an IBM-compatible 486 machine. By initializing acquisition of the LDV data simultaneously with the acquisition of data from the pressure transducers, the location of the separation shock wave relative to the two pressure transducers can be determined for each LDV realization because each velocity measurement also has an absolute time stamp, accurate to within one microsecond, recorded at the time of acquisition. Thus, during data analysis, each LDV measurement will be sorted according to the region in which the shock was located when the LDV measurement was acquired. By comparing the ensemble-averaged flowfield quantities derived from the LDV measurements taken while the separation shock was in the region between the two transducers with the ensemble-averaged flowfield quantities computed from all of the LDV measurements, the effect of the unsteady separation shock wave motion on the mean velocity and turbulent statistical data can be determined.

The data acquisition system for the pressure transducers is based around a Macintosh IIfx computer equipped with 32 MBytes of RAM, a 160 MByte internal hard disk drive, a National Instruments Model NB-A2000 Analog-to-Digital (A/D) converter, and a MicroNet Technology Model SB-1000 external hard disk drive having a storage capacity of approximately 1 GByte. Data acquisition via the A/D converter is controlled by a National Instruments Model NB-DMA2800 Direct Memory Access Interface Board. LabVIEW 2, an icon-based computer language written by National Instruments, is used exclusively to acquire and analyze the pressure data. This data acquisition system is capable of simultaneously sampling two channels at a rate of 166,667 samples/sec per channel for 8.5 minutes (longer than the blowdown time of the tunnel) before overwriting the allocated memory buffer. Currently, LabVIEW programs based upon the two-threshold algorithm [37,38] are being written to analyze the pressure data.

The conditional analysis technique outlined above will work in principle because the frequency spectrum of the unsteady separation shock wave motion, although being broadband, is centered around 1 kHz or less as shown in the power spectral density estimate of Figure 10. The data used to create Figure 10 were taken with the pressure data acquisition system by sampling one

of the flush-mounted pressure transducers located in the intermittent region at a rate of 416,667 samples/sec. The resulting time history was then digitally low-pass filtered at 100 kHz and FFT calculations using the split-radix algorithm were performed on each of 183 records, where each record consists of 16,384 data points. The power spectral density estimate is plotted as f·G(f) versus f on linear-log axes [39] as shown in Figure 10.

Once the LabVIEW conditional analysis programs have been completed, acquisition of the two-component conditionally sampled LDV data will commence. Results of these measurements will be reported in detail in future publications.

CONCLUSIONS

The current paper describes an experimental investigation of a PIBLS flowfield produced by the interaction between two nonparallel, supersonic streams in the presence of a finite thickness base. The purpose of the study is to gain a better understanding of the extent to which the fluid dynamic mechanisms and interactions present in the PIBLS flowfield influence the turbulence properties of the flow. A two-stream, supersonic wind tunnel, incorporating a two-dimensional planar geometry and operating in the blowdown mode, was specifically designed to produce a PIBLS flowfield. Preliminary experiments have demonstrated that the wind tunnel is capable of producing a wide range of PIBLS flowfields by simply regulating the stagnation pressure of the lower stream (jet flow) relative to the upper stream (freestream flow). One PIBLS flowfield has been chosen in which to conduct a detailed set of measurements. This flowfield has its separation point located about $6\delta_0$ upstream of the base corner. A detailed study of this PIBLS flowfield is underway using schlieren photography and shadowgraph pictures, surface streakline visualization, surface static pressure measurements, and two-component, coincident LDV measurements.

Unfortunately, the separation shock wave associated with the PIBLS flowfields is unsteady. The streamwise extent of the unsteadiness was estimated from schlieren observation to be on the order of several boundary layer thicknesses. This unsteadiness poses a problem when making LDV measurements because it is impossible to distinguish between velocity fluctuations caused by the turbulent eddies and velocity fluctuations caused by the gross movement of the separated region. Fortunately, this problem is not insurmountable. A conditional sampling technique for acquiring and analyzing the LDV data is currently under development using surface static pressure measurements taken from fast-response pressure transducers as a means of tracking the separation shock wave motion. This technique effectively reduces the length scale of the unsteadiness by eliminating from the data analysis any LDV measurements that are recorded when the shock wave is outside the region confined between the two pressure transducers.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the U.S. Army Research Office under Contract No. DAAL03-90-G-0021 with Dr. Thomas L. Doligalski as Contract Monitor.

REFERENCES

1. Salmi, R. J., "Effects of Jet Billowing on Stability of Missile-Type Bodies at Mach 3.85," NASA TN D-284, June 1960.

2. Hinson, W. F. and Falanga, R. A., "Effect of Jet Pluming on the Static Stability of Cone-Cylinder-Flare Configurations at a Mach Number of 9.65," NASA TN D-1352, September 1962.

3. Goethert, B. H., "Base Flow Characteristics of Missiles with Cluster-Rocket Exhausts," Aerospace Engineering, Vol. 20, No. 3, March 1961, pp. 28-29, 108-117.

4. Alpinieri, L. J. and Adams, R. H., "Flow Separation Due to Jet Pluming," AIAA Journal, Vol. 4, No. 10, October 1966, pp. 1865-1866.

5. Deep, R. A., Henderson, J. H., and Brazzel, C. E., "Thrust on Missile Aerodynamics," Report No. RD-TR-71-9, U.S. Army Missile Command, Redstone Arsenal, Alabama, May 1971.

6. James, C. R., "Aerodynamics of Rocket Plume Interactions at Supersonic Speeds," AIAA Paper No. 81-1905, AIAA Atmospheric Flight Mechanics Conference, Albuquerque, New Mexico, August 1981.

7. Agrell, J. and White, R. A., "An Experimental Investigation of Supersonic Axisymmetric Flow Over Boattails Containing a Centered Propulsive Jet," Technical Note AU-913, The Aeronautical Research Institute of Sweden (FFA), December 1974.

8. White, R. A. and Agrell, J., "Boattail and Base Pressure Prediction Including Flow Separation for Afterbodies with a Centered Propulsive Jet and Supersonic External Flow at Small Angles of Attack," AIAA Paper No. 77-958, AIAA/SAE 13th Propulsion Conference, Orlando, Florida, July 1977.

9. Boggess, A. L., "An Investigation of the Unsteady Flow Associated with Plume-Induced Flow Separation," Bureau of Engineering Research Report No. 149-02, University of Alabama, July 1972; also available as NASA CR-112218.

10. Doughty, J. O., "Effects of Periodic Plume Pulsing on the Flow Field Generated by Plume Induced Flow Separation," Bureau of Engineering Research Report No. 164-02, University of Alabama, December 1973.

11. Doughty, J. O., "A Study of a Plume Induced Separation Shock Wave, Including Effects of Periodic Plume Unsteadiness," Bureau of Engineering Research Report No. 207-02, University of Alabama, October 1976; also available as NASA CR-150170.

12. Agrell, J., "An Experimental Survey of a Separated Region on a Conical Afterbody in a Supersonic Free Stream," Report No. TN-AU-1187, The Aeronautical Research Institute of Sweden (FFA), October 1978.

13. Agrell, J., "Wind Tunnel Investigation of Separated Flow Over an Afterbody in Supersonic Axisymmetric Stream Utilizing One-Component Laser-Doppler-Velocimetry," Technical Note 1983-10, The Aeronautical Research Institute of Sweden (FFA), 1983.

14. Pira, K. and Agrell, J., "LDV Measurements in the Separated Region Bounded by Supersonic Flows at a Rocket Afterbody," In: International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF), Saint-Louis, France, September 1983.

15. Alber, I. E. and Lees, L., "Integral Theory for Supersonic Turbulent Base Flows," AIAA Journal, Vol. 6, No. 7, July 1968, pp. 1343-1351.

16. Chapman, D. R., "An Analysis of Base Pressure at Supersonic Velocities and Comparison with Experiment," NACA TN 2137, July 1950.

17. Korst, H. H., Page, R. H., and Childs, M. E., "A Theory for Base Pressures in Transonic and Supersonic Flow," ME Technical Note 392-2, Mechanical Engineering Department, University of Illinois, March 1955.

18. Klineberg, J. M., Kubota, T., and Lees, L., "Theory of Exhaust-Plume / Boundary-Layer Interactions at Supersonic Speeds," AIAA Journal, Vol. 10, No. 5, May 1972, pp. 581-588.

19. Fox, J. H. and Bauer, R. C., "Analytical Prediction of the Base Pressure Resulting from Hot, Axisymmetric Jet Interaction in Supersonic Flow," AIAA Paper No. 81-1898, AIAA 8th Atmospheric Flight Mechanics Conference, Albuquerque, New Mexico, August 1981.

20. Addy, A. L., "Plume-Induced Free-Stream Separation During Powered Supersonic Flight: A Computer Program and Representative Results," Report No. RD-72-20, U.S. Army Missile Command, Redstone Arsenal, Alabama, December 1972.

21. Addy, A. L., Korst, H. H., White, R. A., and Walker, B. J., "A Study of Flow Separation in the Base Region and Its Effects During Powered Flight," AGARD Conference on Aerodynamic Drag, CP-124, April 1973.

22. Wagner, B., "Jet-Afterbody Interference on Missiles in Supersonic Flow," AGARD Conference on Ramjets and Ramrockets for Military Applications, CP-307, October 1981.

23. Diewert, G. S., "Supersonic Axisymmetric Flow Over Boattails Containing a Centered Propulsive Jet," AIAA Journal, Vol. 22, No. 10, October 1984. pp. 1358-1365.

24. Fox, J. H., "Predicting Plume-Induced Separation on Bluff-Base Bodies," AIAA Paper No. 84-0315, AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, January 1984.

25. Deiwert, G. S., Andrews, A. E., and Nakahashi, K., "Theoretical Analysis of Aircraft Afterbody Flows," AIAA Paper No. 84-1524, AIAA 17th Fluid Dynamics, Plasma Dynamics, and Lasers Conference, Snowmass, Colorado, June 1984.

26. Sahu, J., "Computations of Supersonic Flow Over a Missile Afterbody Containing an Exhaust Jet," Journal of Spacecraft and Rockets, Vol. 24, No. 5, September-October 1987, pp. 403-410.

27. Korst, H. H. and Tripp, W., "The Pressure on a Blunt Trailing Edge Separating Two Supersonic Two-Dimensional Air Streams of Different Mach Number and Stagnation Pressure but Identical Stagnation Temperature," Proceedings of the Fifth Midwestern Conference on Fluid Mechanics, 1957, pp. 187-199.

28. Tripp, W., "The Base Pressure Behind a Blunt Trailing Edge for Supersonic Two-Dimensional Flow; Approaching Streams Having the Same Stagnation Temperature but

Dissimilar Mach Numbers and Stagnation Pressures," Ph.D. Thesis, University of Illinois, Urbana, Illinois, 1956.

29. Addy, A. L., "Experimental-Theoretical Correlation of Supersonic Jet-on Base Pressure for Cylindrical Afterbodies," Journal of Aircraft, Vol. 7, No. 5, September-October 1970, pp. 474-477.

30. Zukoski, E. E., "Turbulent Boundary-Layer Separation in Front of a Forward-Facing Step," AIAA Journal, Vol. 5, No. 10, October 1967, pp. 1746-1753.

31. Buchanan, T. D., "Study of Flow Separation on Missile by Jet Plume," M.S. Thesis, University of Tennessee, Tullahoma, Tennessee, August 1967.

32. Gramann, R. A. and Dolling, D. S., "Interpretation of Separation Lines from Surface Tracers in a Shock-Induced Turbulent Flow," AIAA Journal, Vol. 25, No. 12, December 1987, pp. 1545-1546.

33. Jones, J. H., "Acoustic Environment Characteristics of the Space Shuttle," NASA TM-X-52876, Space Transportation System Technology Symposium, Volume 2: Dynamics and Aeroelasticity, July 1970, pp. 285-300.

34. Wilkinson, C. L., "Heat Transfer Within Plume-Induced Flow Separation Region of Saturn 5," Paper No. ASME-69-WA/HT-18, ASME Winter Annual Meeting, Los Angeles, California, November 1969.

35. Raghunathan, S., Hall, D., and Mabey, D., "Alleviation of Shock Oscillations in Transonic Flow by Passive Controls," AIAA Paper No. 90-0046, AIAA 28th Aerospace Sciences Meeting, Reno, Nevada, January 1990.

36. Kussoy, M. I., Brown, J. D., Brown, J. L., Lockman, W. K., and Horstman, C. C., "Fluctuations and Massive Separation in Three-Dimensional Shock-Wave / Boundary-Layer Interactions," Second International Symposium on Transport Phenomena in Turbulent Flows, Tokyo, Japan, October 1987.

37. Dolling, D. S. and Brusniak, L., "Separation Shock Motion in Fin, Cylinder and Compression Ramp-Induced Turbulent Interactions," AIAA Journal, Vol. 27, No. 6, June 1989, pp. 734-742.

38. Brusniak, L., "Evaluation of Conditional Sampling Methods for Analyzing Separation Shock Motion," AIAA Paper 88-0091, AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, January 1988.

39. Dolling, D. S. and Smith, D. R., "Unsteady Shock-Induced Turbulent Separation in Mach 5 Cylinder Interactions," AIAA Paper No. 88-0305, AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, January 1988.

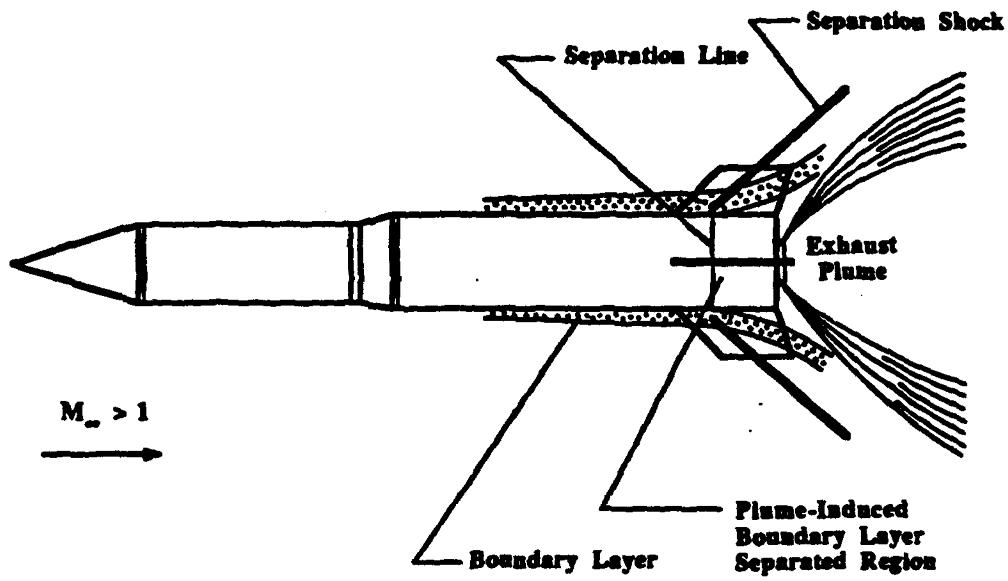

Figure 1. Typical PIBLS Phenomenon Occurring on a Missile

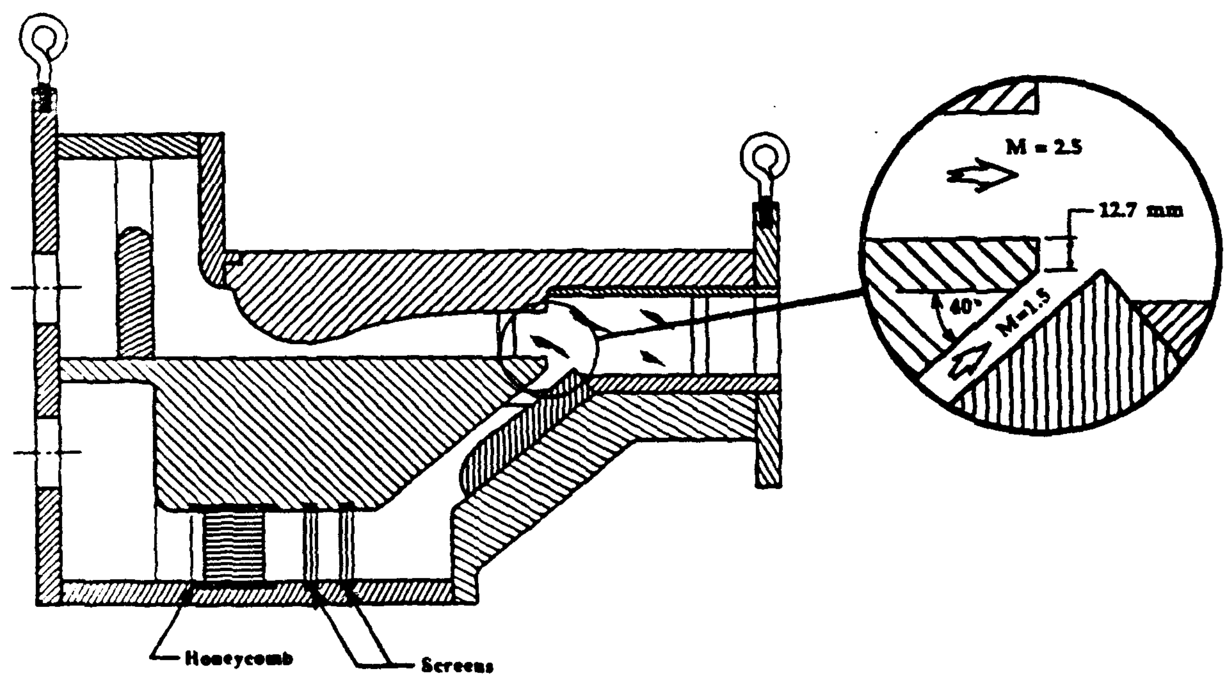

Figure 2. Cross Sectional View of the PIBLS Wind Tunnel

Figure 3. Photograph of the PIBLS Wind Tunnel

Figure 4. Typical Schlieren Photograph of PIBLS Flowfield

Figure 5. Typical Shadowgraph of PIBLS Flowfield

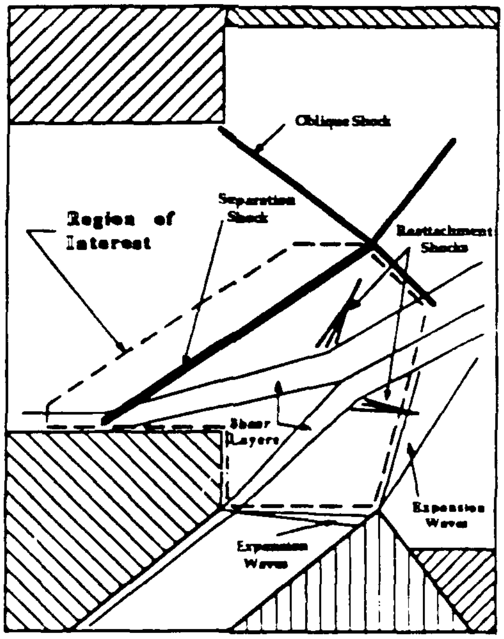

Figure 6. Region of Interest in PIBLS Flowfield

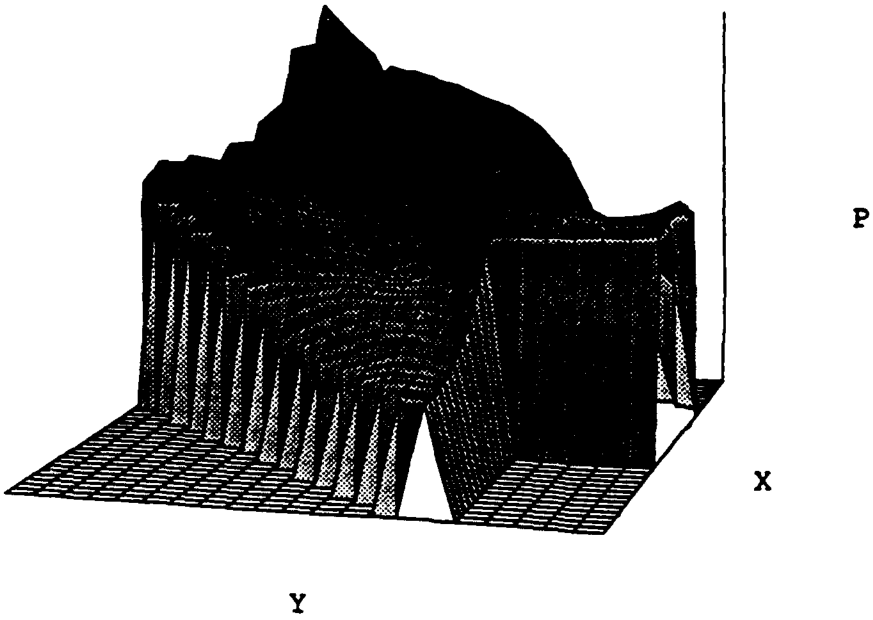

Figure 7. Surface Contour Plot of the Mean Static Pressure Field

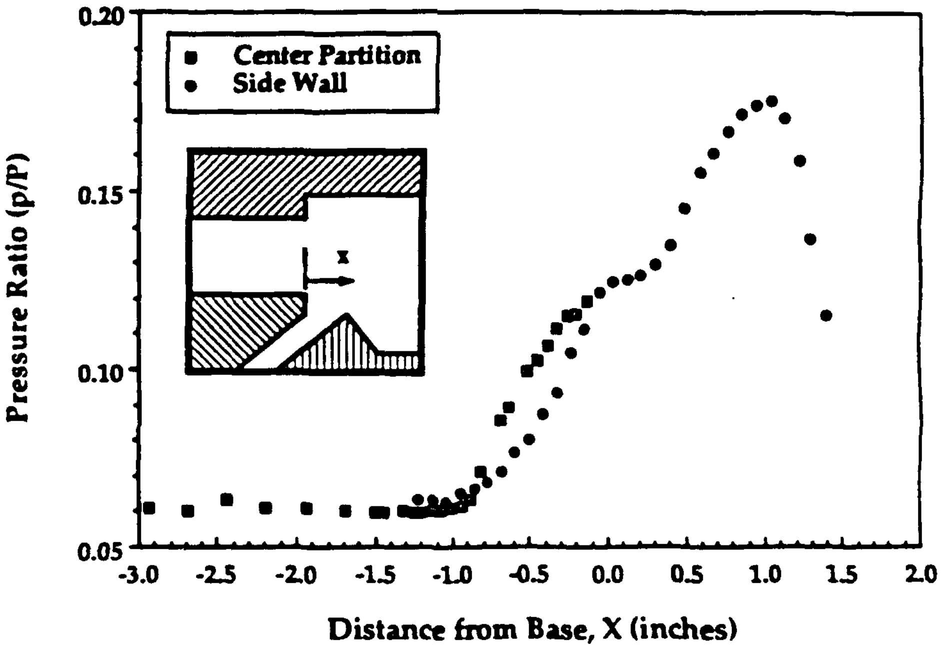

Figure 8. Streamwise Distribution of the Mean Static Pressure Along/Near the Center Partition

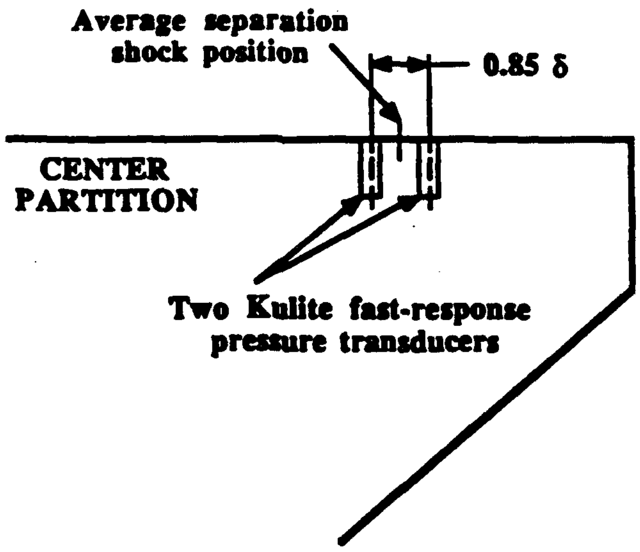

Figure 9. Fast-Response Pressure Transducer Mounting Locations

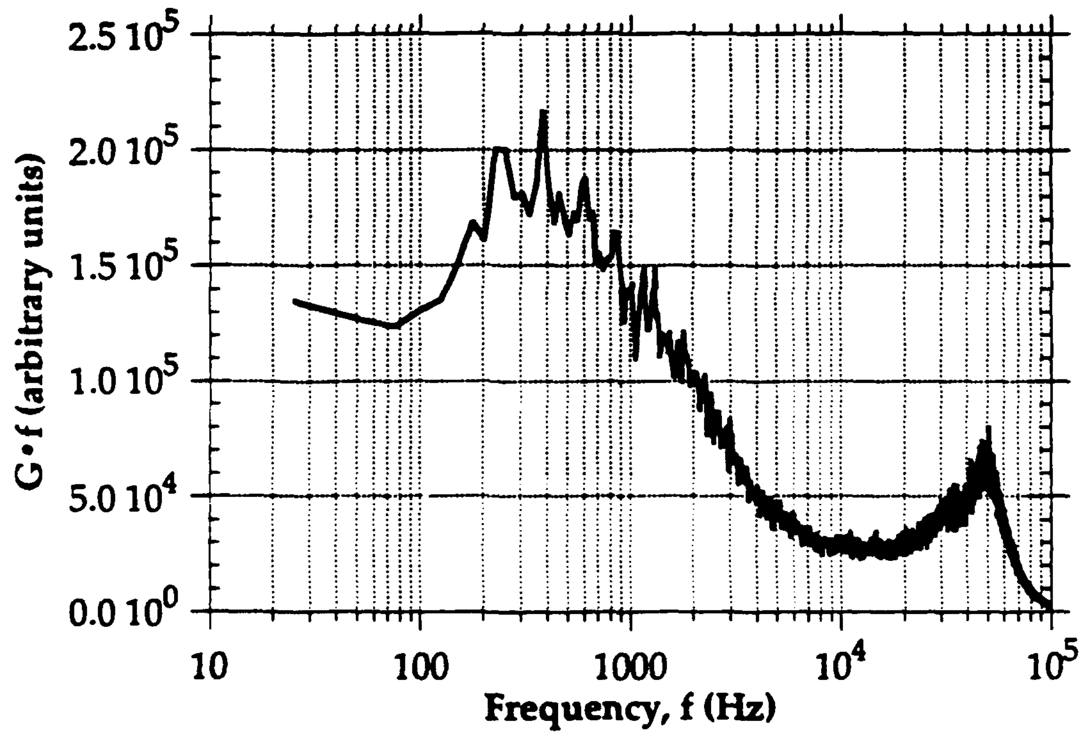

Figure 10. Power Spectral Density Estimate of the Pressure Signal in the Intermittent Region